LIGHTER, STRONGER, MORE AFFORDABLE

DARPA's Quests in the Realm of Materials Science

By Steve Miller

DARPA's imperative for radical innovation for U.S. national security is probably nowhere more dramatically illustrated than in the agency's long and prominent history of materials research – including invention of the very field of materials science – to achieve its defense objectives.

DARPA – created as the Advanced Research Projects Agency, or ARPA – involvement in space marked the inception of materials science. "From the beginning, materials have been a key element of space exploration," said Barbara McQuiston, director of the Strategic Technology Office. "Getting into space requires materials that are light, and yet able to withstand the demands of getting into orbit."

Development of new materials was central to ARPA's work from the earliest days. "Materials are part of our mandate," said Defense Sciences Office (DSO) Deputy Director Leo Christodoulou. "From the beginning, materials research has been one of the core competencies of DARPA. Even the term 'materials science' was coined at DARPA to describe an approach that did not previously exist."

An incremental approach to materials development simply would not work: DARPA's work would have to be revolutionary; technology questions that had never been addressed before would "have to be taken off the table." DARPA's approach to materials research had to be very different than the traditional "stove-piped" metallurgy, ceramics, and polymer research because the challenges the agency and the nation faced were different. High-performance aircraft must not only withstand high stresses but, at the same time, achieve and maintain minimal detectability. The Army's need for a tank weighing one-third of the Abrams without sacrificing offensive or defensive capabilities demands bridging very large research gaps. Naval vessels built from life-of-ship materials, with life-of-ship coatings and surfaces, would profoundly affect U.S. Navy fleet operations, maintenance, and readiness.

A NEW APPROACH

Although humans have used, studied, and improved materials since before the beginning of the historical record, materials research as a multidisciplinary thrust is a relatively young science. Prior to the 1960s, a number of well-developed scientific endeavors independently looked at different material classes. Metallurgy, ceramics science, polymer chemistry – each looked at matter in a different way, delving into the development and characterization of a particular type of substance. Each field had its own language, tools, and successes and each had limits described by the physical characteristics of the material that it studies. Until recently, for example, the concept of an organic electrical conductor was not widely and seriously examined.

As a result of DARPA research initiatives, the study of materials has changed drastically in the past half-century. The field of materials science, created at DARPA, has brought the disparate fields of metallurgy, ceramics, polymers, and most recently, biology, together and added other disciplines such as "first principles," computational tools that serve to characterize electronic structures responsible for many materials properties. "In the past, the researcher confronted with a challenging application would look at a stock of possible materials and ask, 'Which one can I use?'" said Christodoulou. "Our materials researchers use a different approach. We ask, 'What do we need to make a material for a particular application?' There is no bias toward what was used in the past."

The resulting research does not follow the traditional progression of basic research to applied research to device development. Instead, the basic research follows varied tracks simultaneously while the engineering and applications functions are incorporated at all stages. Instead of a focused series of incremental advances, the team seeks the unexpected breakthrough from the combination of viewpoints. The key to advancement is bringing together a team that is aware of the science and at the same time cognizant of the overall needs of the military application.

The overall approach to this materials research was summarized in *Materials Research to Meet 21st Century Defense Needs* by the National Research Council of the National Academies: "Despite this diversity, the recommendations resulting from this effort can be summarized into four principal themes: Design of materials, devices, and systems assisted by computation and phenomenological models of materials and materials behavior; Convergence, combination, and integration of biological, organic, semiconductor/photonic, and structural materials; Discovery and characterization of new materials with unique or substantially improved [50 percent] properties; and New strategies for synthesis, manufacture, inspection, and maintenance of materials and systems."

A Fighter Squadron 114 (VF-114) F-14A Tomcat aircraft. The F-14 Tomcat was one of the first U.S. military aircraft to employ man-made materials, in this case boron fiber in its horizontal stabilizers.

Lt. Steve Gozzo

A HISTORY OF MATERIALS ADVANCES

One of DARPA's early materials success stories was the development of nickel superalloys in the 1960s. Turbine engines place extreme stresses on metallic components, especially turbine disks and blades. In addition, the blades must perform for extended periods at very high temperatures. The need for high-temperature strength, stability after prolonged high-temperature exposure, and oxidation resistance led to a new class of nickel-based alloys, termed "superalloys." Several aspects of alloy design were critical in making an alloy that could function in the brutal environment of a jet engine. Superalloys contain primarily nickel, alloyed with chromium, aluminum, titanium, cobalt, and sometimes traces of as many as a dozen other elements. While the composition is important, many of the desirable properties of the alloy depend on the development of crucial second phases (e.g., gamma and gamma prime), a feature that was not readily determined prior to the electron microscope. Of course, research into nickel superalloys did not stop with the development of the first suitable turbine material. Continual improvements have led to single-crystal turbine blades, capable of operating at temperatures close to the melting point of nickel. Applications of superalloys today include gas turbines, rocket engines, and high-temperature applications in chemical and petroleum plants. This early example of the integration of engineering principles and chemical design provided a model for future research efforts to make reliable materials for civilian as well as defense applications.

While the superalloys developed as part of the DARPA mission greatly improved an existing material, nickel alloy, some materials research leads to entirely new materials, completely different from anything that had previously existed. This is the case with carbon-fiber composites. Although everyone today is familiar with the use of carbon composites in sports equipment, they are a recent product of materials research. The first high-strength carbon fibers came into existence in the 1950s. It did not take long for the military to realize that a very lightweight material with greater tensile strength than steel and a high heat-tolerance held great potential for constructing the bodies and structural components of stronger and lighter aircraft. Realizing the potential was only the first step. To make an actual structural composite, DARPA brought together the efforts of chemists, engineers, and polymer scientists, among others. Today, these composites are essential parts of golf clubs, bicycles, and boats. As the price of gasoline rises, it can be expected that more and more automobile components will be built of carbon-fiber composite, its light weight increasing the fuel efficiency of the car. Carbon-fiber composites are considered one of the greatest engineering achievements of the 20th century by the National Academy of Engineering.

DARPA's continuing search for low-cost titanium solutions could reap huge dividends for the American military as well as the civilian world. The agency's efforts to reduce the cost of titanium could mean this material, superior for military applications, as in the groundbreaking titanium construction of the SR-71 Blackbird pictured here, could become more widely available.

More recently, DARPA has attempted to deal with the fact that military equipment needs to go on a diet – it's generally too heavy. Accordingly, weight reduction in materials has become an important research focus for DSO. One approach to weight reduction is the design of materials that are themselves lighter than the alternatives. A second, equally important focus at DARPA has been the development of multifunctional materials, where a single material does more than one job. The result is a reduction in the number of component parts of a system. For example, structural batteries have been developed that reduce weight and complexity by building energy storage directly into the load-bearing structure; the case that protects the functional elements of the device also becomes its battery. The development of multifunctional materials relies on the detailed understanding and control of the properties of materials. Frequently the multifunctionality is achieved by combining two or more basic materials to take advantage of their interactions.

Materials research is not limited to the structural materials that form the backbones and shells of large objects. Gallium arsenide, another material that did not exist prior to its development in DARPA's multidisciplinary materials research efforts, offers advantages to an entire range of semiconductor-device manufacturers. Because of its low noise signature, heat stability, and resistance to radiation, gallium arsenide finds frequent application in communications devices where low signal strength and tough physical environment can be problems, such as battlefield communications. Of course, the same low noise makes gallium arsenide indispensable for cell phone communication companies and NASA as well. While gallium arsenide is already widely used in high-frequency communication, fast-switching devices, and cutting-edge computing applications, DARPA continues to fund new research applications that are capable of taking advantage of its characteristics. These include optical devices, such as night vision scopes and high-efficiency solar energy cells. Other projects focus on the fabrication of gallium arsenide devices and cells to reduce their cost to levels competitive with the cost of other semiconductor devices.

CURRENT FOCUS AND FUTURE PROJECTS

"At the Defense Sciences Office, we are not just looking at materials anymore," said Christodoulou. "Now the focus is on material systems. We don't just look at the chemistry but also the topology – how things are put together. How can you take two ordinary materials and put them together in a special way to create new functions?"

The most complex and most integrated examples of materials systems exist around and within us. In living things, nature has constructed the most elegant examples of putting materials together to solve complicated problems. Many of the goals of defense research – mobility, camouflage, armor, and sensing – are handled by organisms in a constant struggle for survival. Materials scientists are currently seeking ways to build self-healing materials. The design of these materials systems, based on the ability of living cells and organisms to repair damage, will build in a functional capacity to repair breaks and tears. Biologically inspired materials are an excellent example of the multidisciplinary research.

As an example of biologically inspired research, an artificial muscle that responded in the same way as its biological analog would allow rapid gains, not only in robot technology, but also in the development of replacement limbs for humans that emulate real arms. Muscles serve many functions at once: They move body parts, sense position, and serve as a structural component of the organism by supporting weight and acting like a spring and damper. While fulfilling all these functions, they remain soft and compliant. DARPA is currently funding research to develop materials that can serve these same functions by looking at what has already been accomplished in nature. Research teams include biologists to characterize the natural functions of muscles; engineers to design and specify the qualities needed in a substitute; chemists, physicists, and polymer scientists to develop the structure of an elastomer that will expand and contract when an electric field is put across it; neurologists to determine the details of the control system tied to the brain; computer scientists to develop the control functions; and myriad other specialists, each of whom brings a different perspective to the puzzle.

Another area in which biology has outpaced technology is the ability to sense the environment. An example is provided by Steven Wax, former director of the DSO. "Let's begin with one of my favorite examples, the Melanophila beetle," he said at the 2002 DARPATech Symposium. "Reproduction is one of the driving forces of nature, and this beetle's reproductive strategy is to lay its eggs in burned-out wood. Because reproduction is key to survival, this beetle has developed the ability to detect forest fires from 60 miles away. Put in defense terms, it has the

The exotic materials that make the F-22 Raptor what it is, from the superalloys in its engines to the carbon fiber, titanium, and other materials in its airframe, were all developed or refined under DARPA-sponsored programs. The Raptor is pictured here performing high-energy maneuvers at an air show.

capability at 0.3 microns wavelength to measure radiative power that translates to 0.003-degrees-Celsius resolution, making it an incredible room-temperature infrared sensor. The organ the beetle uses to accomplish this has been characterized. It is believed that the mechanism is the expansion of the sphere due to absorption of infrared radiation that causes a one nanometer deformation of the dendritic tip and provides a signal to the beetle." This and other natural sensors are currently being investigated by DARPA's interdisciplinary teams.

Nature has provided us with a practically limitless range of special abilities, materials, and systems as sources of research inspiration. As another example, oceanographers, biologists, engineers, and chemists all play a role in determining how diatoms and sponges build extremely strong structural materials using simple chemical compounds. Ongoing materials projects led by DARPA include the mechanism of insect flight, the ability of a gecko to climb a wall, the optics of vision in fish and insects, and the glue used by a barnacle to attach itself to a surface while surrounded by seawater.

One of the strengths of DARPA materials research is that no idea is too improbable to become a research subject. For example, what could you do with the invisibility cloak of fantasy literature? Although the question itself may seem to penetrate the realm of fantasy, current research into negative refractive index materials could be the initial steps toward bending light around an object or person. These materials were first proposed theoretically in 1967 and actually built in 1999. More recently, professor David Smith, who was originally sponsored by DARPA while at the University of California at San Diego and who is now at Duke University, has demonstrated an invisibility cloak for microwaves using negative index of refraction materials, according to a *Scientific American* article.

Negative index materials are an example of metamaterials (a term coined at DARPA), which consist of man-made structures wherein wires and small coils are arranged in a three-dimensional array similar to molecules in an ordinary material. These entities are designed to interact with the electric and magnetic vectors of incoming radiation in such a manner as to give the properties of a negative refractive index, a property that no known ordinary material has. As an example of the revolution these materials have created in the optics field, it has recently been demonstrated that they can be used to build lenses whose resolution far exceeds the diffraction limit of the wavelength of light being used for the observation. Metamaterial research, while still in its early stages, promises to grow in importance at DARPA in the future.

LOW-COST TITANIUM

While devices such as an invisibility cloak or a case for a communication device that also serves as its battery may have large "gee-whiz" factors, some initiatives are less catchy but equally important to defense applications. For example, one of the most important structural materials for military applications has been studied since the 1960s. For many applications, titanium is superior to any other metallic or composite materials. It is strong, light, and highly resistant to corrosion. Unfortunately, titanium is also expensive despite the fact that it is the fifth most abundant element in Earth's crust. "What would happen if high-grade titanium was available at $3.50 per pound?" Christodoulou asked. The answer is that it would become the metal of choice for most defense structural applications.

The fundamental science of titanium came from DARPA-funded research in the early 1960s. More than 40 years ago, the SR-71 Blackbird was built almost entirely of titanium because of the material's unique features, particularly its light weight. These planes served through the first Gulf War. If the cost of titanium could be sufficiently reduced, it is likely that many military and most civilian aircraft would be built of titanium. Ships built of titanium, which is extremely resistant to corrosion by seawater, would spend substantially less time in drydock undergoing renovations. Titanium ground vehicles would be stronger, faster, and easier to transport.

If titanium is superior to steel and aluminum for so many applications, why is its use so limited? The answer is cost and availability. Military-grade titanium costs more than $35 per pound, much more than alternative materials. And, it sometimes takes years to fill a large order for titanium. Unlike precious metals, titanium is expensive not because of its rarity but because of the cost to remove it from the ground and process the ore into useful metal and alloys. Christodoulou points out that in the 1800s, aluminum was considered a precious metal. Due to significant changes in processing technology, aluminum foil is now a disposable item in every kitchen. He is seeking a similar revolution in the extraction process for titanium.

DoD photos

Above, left: One of DARPA's early material success stories was the development of nickel superalloys in the 1960s. Such superalloys provided high-temperature strength, stability, and light weight inside the turbine stages of jet engines, and improvements to such materials over the years continue to bear fruit today. Above, right: Using an understanding of the physics of failure mechanisms, the Prognosis program enables evaluations of remaining useful life for aircraft and aircraft engines. With the ability to reliably predict the lifetimes of these components, commanders can continue to use combat systems that otherwise would have been removed from service.

Photo courtesy of DARPA

The DARPA Initiative in Titanium program, now in its second phase, seeks to develop and establish revolutionary industrial production and processing methodologies and capabilities for titanium metal and its alloys. The overall goals of this program are to: (1) establish a U.S.-based, high-volume, low-cost, environmentally benign production capability enabling widespread use of titanium and its alloys; (2) develop and demonstrate unique, previously unattainable titanium alloys, microstructures, and properties that enable new high-performance applications; and (3) develop meltless consolidation techniques that will provide low-cost billet, rod, sheet, and plate products that match the properties of traditional wrought titanium mill products. Currently, efforts are aimed to produce high-quality, military-grade titanium at target costs of less than $3.50 per pound.

In typical DARPA style, there is no preconceived notion of what is important to reduce the cost of titanium. Any idea, no matter how off-the-wall it may sound, is fair game for research. Also, in typical DARPA style, simultaneous research is looking for ways to find a better form of titanium, or even a substitute, for defense applications.

Notwithstanding all the improvements that have been made in structural materials through research funded by DARPA and by others, materials do accumulate damage as they are used (a phenomenon known as "fatigue"). Fatigue can sometimes reach the point of crack formation, causing an engine disk or blade to fail. Failures of this type can, of course, lead to engine and perhaps platform failure. For this reason the Air Force and other branches of the military spend millions of dollars each year doing routine inspections and engine tear-downs to avoid such catastrophes. However, since damage accumulation is predictable based on the actual loads experienced by each aircraft, DARPA, in a desire to reduce maintenance costs, asked the question, "Is it possible, using what is known about 'physics of failure' mechanisms, to predict the lifetime of engine and structural components and relay that information to the pilot or field commander so the platform can be throttled back if necessary, providing time to complete a mission?" To find the answer, DARPA is currently funding the Prognosis program. This program aims to demonstrate the capability to forecast future state and capability, and thus manage individual aircraft based on their true state rather than on some statistical, fleet-wide basis. "This would mean that we could carry out maintenance on a need basis rather than repairing 1,000 aircraft to make sure that we fix the one that is in need of repair," Christodoulou explained.

While these examples provide a quick look at materials research at DARPA, they barely scratch the surface. Books could be (and have been) written about materials investigated by DARPA and still a complete description would be elusive. The spectrum of materials under investigation is clearly not limited to structural components. Semiconductors, superconductors, thermoelectrics, and advanced optics are all important current research topics. In fact, anything that makes devices lighter, faster, or better is fair game for a DARPA project.